A MODIFIED AERATION PROCESS FOR PROMOTING NUTRIENT REMOVAL USING WATER HYACINTH TO TREAT SEWAGE

XIANG ZHONG LI*, XIAODI HAO and DA YUE ZHU

Department of Civil & Structural Engineering, The Hong Kong Polytechnic University,

Hung Hom, Kowloon, Hong Kong, E-mail: cexzli@polyu.edu.hk, Fax: +852 2334 6389

ABSTRACT

To upgrade some conventional aeration processes, a lab-scale system for promoting nitrogen and phosphorus removals was set up and studied through a series of experiments, in which water hyacinth was planted on the surface of the mixed liquor in aeration tanks. The main purpose of this study was to evaluate the effects of (1) aeration, (2) organic load (chemical oxygen demand) and (3) residence time on the nutrient removal efficiency of a water hyacinth based system for the purification of raw and settled sewage wastewaters. The experiments indicated that the aeration with airflow intensity of 4 l min^{-1} can provide enough oxygen supply but no significant disturbance on water hyacinth growth. The water hyacinth grew better in a moderate organic strength of chemical oxygen demand (COD) = 18 - 80 mg l^{-1}. In this study, it was observed that chlorosis of water hyacinth occurred under the conditions of nutrient deficiency, and its possible reason due to iron (Fe) deficiency was analyzed. The increase of solids retention time (SRT) from 5 to 20 days was of benefit for organic and nutrient removals. The system demonstrated a high performance of nitrogen and phosphorus removals up to 86 % and 80 % respectively from the raw sewage, which are far better than that in floating aquatic macrophyte-based treatment systems (FAMS) and wetland systems. Dissimilation via nitrification and denitrification was considered as a major pathway of N removal, and assimilation via plant uptake was thought to be responsible for more than a half of P removal in the designed system.

Keyword: Nutrient removal, water hyacinth, aeration, uptake of plant, chlorosis

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* Corresponding author, Mailing address: Dept. of Civil & Structural Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, Fax: (852) 2334 6389

INTRODUCTION

Nutrient removal from wastewater has become an important issue nowadays due to the problems of eutrophication in many areas of the world. Accordingly a trend of tightening up wastewater discharge standards for nutrient control is being forced internationally. For example, Europe has made a step forward due to the international agreements from the Rhine Action Program (RAP) and the North Sea Action Program (NSAP) [1-2]. Traditionally, conventional activated sludge processes (CASPs) used in most existing wastewater treatment plants (WWTPs) were designed for BOD/COD removal only. How to upgrade these WWTPs including a function of nutrient removal to comply with the new standards is an important issue for engineers. In the last decade, a lot of upgrading processes for nutrient removal have been developed and applied in Europe and other developed countries [2-8]. However, those developed techniques may not be suitable for application to all WWTPs in the developing countries due to their expensive upgrading costs. Meanwhile, the modification of the existing WWTPs may require a large footprint, which could be highly restricted in some places such as Hong Kong.

Although some existing conventional activated sludge processes (CASPs) have a potential for nitrogen removal via nitrification/denitrification after simple modifications, they are generally difficult for phosphorus removal unless some chemicals are added. A recent lab-research demonstrated that nitrification and denitrification associated with photosynthesis were a main pathway for permanent nitrogen removal from NBTPs such as lagoon [4]. But phosphorus removal from lagoons to a great extent has not yet reported [11]. On the other hand, many natural biological treatment processes (NBTPs) such as lagoons or oxidation ponds as low-cost techniques have also been rapidly developed in many countries such as China and North America [9-10]. They generally have limited capacity and efficiency for nutrient removal and need to be upgraded with affordable costs. As well known, aquatic plants can uptake both nitrogen and phosphorus from water. Nogales et al. demonstrated optimal effectiveness in reducing N, P and K from a secondary sewage effluent using water hyacinth [12]. In practice, NBTPs with aquatic plants can be also found. The floating aquatic macrophyte-based treatment system (FAMTS) and the constructed wetland system (CWS) have been proved to be successful in wastewater treatment, especially in nutrient removal [14-16]. Although FAMTS and CWS have certain advantages of low capital costs, simple operation, ease of maintenance, less energy consumption and little chemical use, low removal efficiency and odor problems are often associated with them. As one of widely used aquatic plants, water hyacinth can grow very quickly in water environment and can be regularly harvested. The harvested water hyacinth wastes can be utilized as animal food, fertilizer, soil conditioner and raw material of pulp and paper [17].

If NBTPs with water hyacinth is aerated or if water hyacinth is planted into existing CASPs to grow, the advantages of NBTPs and CASPs may be combined, so that nitrification/denitrification by microorganisms and uptake of phosphorus by aquatic plants might be of benefit for nutrient removal. Under this consideration, an aeration-water hyacinth system was thus designed in this study by planting water hyacinth in an intensified aeration process. It was aimed to conduct a series of lab-scale experiments to ascertain the parameters affecting the growth of water hyacinth in sewage and the parameters affecting overall nutrient removal efficiency in the designed aeration-water hyacinth process.

MATERIALS AND METHODS

Equipment and Materials

A total of three experiments were carried out in this study, in which 16-litre plastic buckets with an effective volume of 11 litters were used as reactors in Experiment 1 and Experiment 2, while 44-litre plastic tanks with an effective volume of 33 litters were used as reactors in Experiment 3. All the reactors were equipped with an aeration device including a T-shape plastic tube with two air-diffusers fixed at the bottom of each reactor. The structure of the reactors is shown in Figure 1. The sewage used in the experiments was collected once a week from a local WWTP in Hong Kong, which contained major domestic and minor commercial and industrial discharges. Water hyacinth (*Eichhornia crassipes* [Mart.] Solms) was collected from a local water pond in Hong Kong. The water hyacinth after collection was first cleaned and rinsed by tap water to remove mud, yellow and senescent tissue, and broken roots. Prior to the experiments, the cleaned water hyacinth was cultivated outdoors in tap water for 10 days. Then the water hyacinth was planted in the reactors filled with either raw sewage or diluted sewage. In the experiments, the reactors were aerated in an alternative cycle of 0.5 hr on and 0.5 hr off. An intensified aeration intensity of 4 l min^{-1} was applied in all the experiments. This aeration-water hyacinth system was operated similar to a Sequencing Batch Reactor (SBR). All experiments were operated outdoors under an ambient temperature.

[Figure 1]

Operating conditions of experiments

Experiment 1 was conducted in five 16-litre buckets, labeled as No. 1, 2, 3, 4 and 5, all of which were planted with water hyacinth. The raw sewage and diluted sewage with different COD concentrations of 200, 100, 50 and 20 mg l^{-1} were filled into Bucket No. 1, 2, 3 and 4 respectively, and tap water with COD concentration of <5 mg l^{-1} was filled into Bucket No. 5. During the experiment period, the buckets were fed in a batch mode. After every 2 or 3 days, the declined COD concentration and the lost amount of water in each bucket was made up by adding raw sewage and tap water to their initial values. The experiment was operated under an ambient temperature of 7-18^{o}C and lasted for 59 days. The operating conditions in Experiment 1 are summarized in Table 1.

[Table 1]

Experiment 2 was carried out in four 16-litre buckets. While three of them, labeled as No. 1, 2 and 3, were planted with the water hyacinth, and the other one labeled as No. 4 was used as a control trial without planting water hyacinth. The four buckets were operated in a continuous-flow mode and the raw sewage was fed as influent with a flow rate of 1.5 l d^{-1}. Bucket No. 1, No. 2 and No. 3 had the solids retention time (SRT) of 20, 10, and 5 days respectively, while Bucket No. 4 had a SRT of 10 days. A hydraulic retention time (HRT) of 6.7 days was applied in all the buckets to perform an extended aeration process. The experiment was operated under the ambient temperature of 12-29^{o}C and lasted for 64 days. The operating conditions in Experiment 2 are summarized in Table 2.

[Table 2]

Experiment 3 was carried out in the six tanks with a larger volume, which were operated as two groups: the tanks labeled as No.1, No. 2 and No. 3 were in Group 1 and the tanks labeled as No. 4, No. 5 and No. 6 were in Group 2. The tanks in Group 1 were employed to treat the diluted sewage, while the tanks in Group 2 were used to treat the undiluted sewage. Among them, Tank No. 2 and No. 6 were the duplicates of Tank No. 1 and No. 5 respectively. Tank No.1, No. 2, No. 5 and No. 6 were planted with water hyacinth and used as the aeration-water hyacinth systems; Tank No. 3 and No. 4 were not planted with any water hyacinth and used as the CASP systems. All the tanks from No.1 to No. 6 were operated in a continuous-flow mode with the same SRT and HRT of 10 days. The settled sewage without dilution was fed to the tanks in Group 1. The settled sewage was diluted with tap water to achieve COD=30 mg l^{-1} first and then fed to the tanks in Group 2. An influent flow rate of 3.3 l d^{-1} was employed in all the tanks. The experiment was operated under an ambient temperature of 19-33^{o}C and lasted for 92 days. During this period, water hyacinth was harvested once on the 54th day. The operating conditions in Experiment 3 are summarized in Table 3.

[Table 3]

Analyses and Measurements

Wastewater samples were collected from each bucket or tank twice a week for the analyses of chemical oxygen demand (COD), biochemical oxygen demand (BOD_5), total Kjeldahl nitrogen (TKN), ammonia nitrogen (NH_4^+-N), total phosphorus (TP), suspended solids (SS) and pH by the standard methods [18]. Suspended biomass was measured by determining the suspended solids in mixed liquor (MLSS) and attached biomass was determined by the following steps:

- take the water hyacinth out of the reactor
- rinse it by clean water carefully
- the amount of SS in the rinsing water was determined as attached biomass

The botanical state of water hyacinth growth, including changes of leaf color, leaf length, length and width of lamina and plant density, was consistently observed and measured during the experiments. The weight of water hyacinth during the experiments was also recorded.

RESULTS AND DISCUSSION

Characterization of sewage

The sewage collected from the WWTP was characterized in the laboratory. Their characteristics are summarized in Table 4.

[Table 4]

Growth of water hyacinth in sewage

COD concentration: In Experiment 1, the 5 buckets from No. 1 to No. 5 maintained the different COD concentrations of 200, 100, 50, 20 and 5 mg l^{-1} respectively. The growth of water hyacinth in the buckets was carefully observed during the experimental period of 59 days. The weights of water hyacinth planted in the buckets before and after the experiment are compared as shown in Figure 2. It was found that the water hyacinth in Bucket No. 1 with the highest COD concentration did not achieve the highest increase in its weight, which means that the COD concentration in the bucket is not in direct proportion to growth of water hyacinth and might be resulted from several factors. Since this experiment was operated with a batch mode, there was the significant fluctuation of COD concentration in the buckets. It was found that a maximum COD variation of 126 mg l^{-1} was achieved in Bucket No. 1, when the declined COD from 74 mg l^{-1} was instantly readjusted to the initial value of 200 mg l^{-1}. This COD variation would result in a sudden change of permeation pressure between the interior and the exterior of root cells, and would further affect water hyacinth growth. The lowest increase of weight was found in Bucket No. 5 as expected, because organic substrate and nutrient elements were insufficient for water hyacinth to grow probably. The experimental results indicate that the COD concentration in the range of 18 – 80 mg l^{-1} in the buckets of No. 2, No. 3 and No. 4 behaved more suitable for water hyacinth to grow. This COD value is also closed to a normal COD concentration of mixed liquor in activated sludge processes and lagoon water in most WWTPs and Lagoons.

[Figure 2]

Chlorosis: In Experiment 1, it was observed that leaf color of the plant in Bucket No. 4 and No. 5 appeared to a little bit yellow after 40 days growth. This chlorosis phenomenon was also confirmed in

Experiment 3, in which the water hyacinth in Bucket No. 1 and No. 2 fed with diluted sewage turned into yellow color after 54 days growth.

The chlorosis phenomenon of water hyacinth planted in sewage has never been reported. But Reddy [19] and Shiralipour *et al*. [20] stated the growing conditions of water hyacinth in cultivated solutions mixed. Chlorosis of water hyacinth in such solutions was supposed for two reasons: either nitrogen deficiency or iron deficiency. The N:P ratio in tissues of water hyacinth was reported to be approximately 6:1 [21] . For the reason, at least a N:P ratio of 6:1 should exist in sewage or diluted sewage for the normal growth of water hyacinth. In practice, municipal sewage can generally meet the required N:P ratio [22]. The influents (both raw and diluted sewage) used in the experiments had the N:P ratios between 7:1 and 10:1 respectively. Therefore, N deficiency seemed not a main reason causing the chlorosis of water hyacinth in the experiments. Alternatively, the concern of Fe deficiency became the main consideration, which may be the only possible factor causing the chlorosis of water hyacinth. Some metal elements such as Fe, Zn, Mn and Cu are generally considered to be essential for growth of aquatic plants [23, 24]. The mechanisms of Fe uptake by plants are different from those of Zn, Mn and Cu [25]. Fe uptake depends on soluble Fe concentration in solutions. Furthermore, solubility of Fe depends on pH values [24]. When pH in solution increases, soluble Fe will be reduced due to precipitation, and then Fe deficiency might occur. Mengel and Kirkby [26] reported that soluble Fe could be decreased by about 1,000 times when pH increased 1 unit, especially in the pH range of 5~9. Therefore, it can be understood that pH may change Fe status in water media even though sewage generally has no a lack of Fe. In this study, it was found that the mixed liquor in the buckets/tanks with the normal-green leaf of water hyacinth had pH of >7.1, whereas those with the yellow leaf of water hyacinth had pH<6.3 (mainly due to nitrification). The lower pH in those buckets/tanks would certainly result in a decrease of soluble Fe, and cause Fe deficiency consequently. Marschner [27] reported that Fe deficiency could certainly cause yellow color of plant leaf and finally result in chlorosis. However, although chlorosis of water hyacinth might be attributed to Fe deficiency in this study, further quantitative research needs to be further carried out as Fe concentration was not measured in the experiments.

Performance of the aeration-water hyacinth system

Solids retention time (SRT): In Experiment 2, three different SRTs of 20, 10 and 5 days were applied in Bucket No. 1, No. 2 and No. 3 respectively with a continuous flow mode. The operating conditions similar to a CASP were maintained. For this reason, higher removal efficiency was expected to appear at a longer SRT. The experimental results to indicate a relationship between SRT and removal efficiency are shown in Figure 3.

[Figure 3]

Although higher removal efficiency appeared with a longer SRT applied, the differences among these removal efficiency were not very distinct. In principle, suspended-growth biomass would increase when SRT was increased, and more biomass would result in higher removal efficiency. Evidently, the results in Experiment 2 did not support this normal appearance even though there was indeed a significant difference of suspended-growth biomass ($MLSS_{mean}$=261, 192 and 141 mg l^{-1}, respectively in the buckets of No. 1, No. 2 and No. 3). In fact, there also was attached-growth biomass in the aeration-water hyacinth system, besides suspended-growth biomass. When water hyacinth grew in the buckets, its root system played a role of supporting medium for biomass to develop as a biofilm. Moreover, the attached-growth biomass was consistently retained in the buckets, which has a long SRT. It means that the SRT used in the system did not indicate the mean lifetime of the attached-growth biomass at all, while it was only applied to the suspended-growth biomass. The long SRT applied to the attached-growth biomass certainly increased total biomass. Under the circumstance, the similar removal efficiency found in the buckets with different SRTs in Experiment 2 should be explained by considering both suspended-growth and also attached-growth biomass for biodegradation of COD in the reactors.

Biomass concentration: In the buckets/tanks planted with water hyacinth, biomass, responsible for biodegradation, should include both the suspended form in the mixed liquor and also the attached form on the roots of water hyacinth. In Experiment 2, the attached-growth biomass in Bucket No. 2 was measured as 2,881 mg, while the MLSS concentrations in Bucket No. 2 and No. 4 were 191 and 227 mg l^{-1}

respectively. If we consider that this 2,881 mg of attached biomass is equivalent to an MLSS concentration of 288 mg l^{-1}, a total amount of biomass in Bucket No. 2 would be significantly higher than that of Bucket No. 4. This was why there was the superiority of Bucket No. 2 to Bucket No. 4. However, it seems that the biomass (microorganisms) only could not to take full responsibility for the higher N and P removals in Bucket No. 2 and the water hyacinth must have functioned for nutrient removal. In Experiment 3, the composition of biomass is also studied as shown in Figure 4. It demonstrates that the amount of attached-growth biomass (60 %) was more than that of suspended-growth biomass (40%) in the tanks with water hyacinth. Therefore, water hyacinth also served as packing material (root carriers).

[Figure 4]

Organic loading: To compare the performance of the aeration-water hyacinth system affected by different organic loading, Experiment 3 was carried out to feed two groups of tanks with settled sewage and diluted settled sewage respectively. The removal efficiency of COD and BOD_5 in Experiment 3 is listed in Figure 5. The lowest removal efficiency of COD and BOD_5 occurred in Tank No. 3 that contained no water hyacinth and a low nutrient concentration (diluted sewage). It could be understood that Tank No. 3 had the least biomass among all the tanks. Tank No. 4, 5, and 6 were continuously fed with the settled sewage with an average COD concentration of 210 mg l^{-1}. After 20 days operation, the COD concentrations in Tank No. 4, 5 and 6 were stabilized as 40, 33 and 34 mg l^{-1} respectively and the water hyacinth grew very well with a healthy green color. However, Thank No. 1, 2, and 3 were fed with the diluted sewage that had lower concentrations of $COD_{inf.}$ = 30 mg l^{-1}, TKN_{inf} = 6.7 mg l^{-1} and $TP_{inf\,.}$= 1.0 mg l^{-1}. Although Tank No. 1 and 2 generated their effluent with lower concentrations of $COD_{eff.}$ = 12 mg l^{-1}, $TKN_{eff.}$ = 3 mg l^{-1} and $TP_{eff.}$ = 0.3 mg l^{-1}, the water hyacinth did not grow well and finally turned into yellow color. This phenomenon indicates that the water hyacinth grew in a difficult condition with this low organic load.

Nitrogen and phosphorus removals: In Experiment 2, Bucket No. 2 with water hyacinth as an aeration-water hyacinth system and No. 4 without the plant as a CASP system were used for a purpose of comparison. The experimental results as shown in Figure 5 indicate that both buckets achieved similar efficiency for BOD and COD removal, but different N and P removals. As shown in Figure 5, the better removals of N and P in the aeration-water hyacinth system compared to the CASP system was achieved in Experiment 2.

[Figure 5]

In Experiment 3, Tank No. 1 and No. 4 were used as the CASP systems and Tank No. 2, No. 3, No. 5 and No. 6 were used as the areation-water hyacinth systems for sewage treatment. To further compare the N and P removing capacities in the two systems, their daily performance data for TKN and TP treatment are shown in Figure 6 and Figure 7 respectively.

[Figure 6]

[Figure 7]

Both of Experiment 2 and 3 fully confirmed the superiority of the aeration-water hyacinth system to the CASP system in nutrient removal. It seems that the function of plant uptake played an important role on the P removal in the aeration-water hyacinth system. Tank No. 4 had the P removal efficiency of only 31.5%, whereas Tank No. 5 achieved the P removal up to 80%. More than a half of P removal in the aeration-water hyacinth system was obviously attributed to planting water hyacinth.

N removal from wastewater in both CASPs and NBTPs has been widely applied or reported [4]. Either in CASPs or NBTPs, nitrification and denitrification are a main pathway of N removal even though assimilation of microorganisms can take up a small part of nitrogen for cell synthesis. Especially under the presence of attached-growth biomass, nitrification and denitrification were intensified in the experiments. As a result, dissimilation was supposed to be a major pathway of N removal in the aeration-water hyacinth system. In addition, nitrogen uptake of plant could also contribute to N removal when water hyacinth was planted. Therefore, a minor pathway caused by uptake of plant could speed up N removal from sewage in the aeration-water hyacinth system.

The general mechanisms of biological phosphorus removal from wastewater are attributed to the discharge of surplus sludge enriched by phosphate, that is, aerobic-uptake and anaerobic/anoxic-release works alternatively [5]. Different from the EBPR (enhanced biological phosphorus removal) system, aerobic and anaerobic/anoxic conditions in the aeration-water hyacinth system occurred alternatively in the identical reactor. Phosphate absorbed by microorganisms during aeration could be released into the mixed liquor again when aeration was off. In addition, nitrate contained in the mixed liquor under the anoxic condition would probably affect the release of phosphate and further control uptake of phosphate under the aerobic condition. As a result, less sludge discharge due to a short HRT of 10 days could not be responsible for the full P removal. For the above reasons, a pathway of P removal in the form of surplus sludge enriched by phosphate played a limited role in the aeration-water hyacinth system. Therefore, uptake of plant by water hyacinth should be a mainly contributing pathway of P removal in the aeration-water hyacinth system. A former study also demonstrated that 13% of total phosphorus removal during non-harvest and 25% of it during harvest were achieved by water hyacinth [13]. As the mentioned above, at least 50% of total P removal was achieved due to uptake of water hyacinth in the aeration-water hyacinth system; the reason was due to harvest once on the 54th day. The experimental results in this study demonstrated that P removal in the aeration-water hyacinth system was very significant. If the plant can be regularly harvested, P will be continuously removed from wastewater. For this reason, the aeration-water hyacinth system may be competitive with some existing upgrading processes, especially under the conditions of a limit of footprints such as in Hong Kong and of using lagoons as the secondary wastewater treatment such as in China and in North America. However, some further research should be carried out to investigate the operational concerns associated with this process, which may involve the disposal of water hyacinth waste generated by regular harvests and the control of a fast growth rate of water hyacinth in summer and a declined reaction rate for wastewater treatment in winter.

CONCLUSIONS

As an innovative process for upgrading of some existing WWTPs and lagoons, the designed system demonstrated a significant enhancement of nutrient removal. Based on the proposed concept and the results obtained in the experiments, the following major conclusions can be drawn:

1. Water hyacinth was suitable to grow in an aerated water environment with a moderate COD concentration in the range of 18 to 80 mg l^{-1}. The intensified aeration intensity of 4 l min^{-1} in this experimental conditions created no significant disturbance to water hyacinth growth.
2. SRT in the range of 5 to 20 days could be of benefit for COD, BOD_5, N and P removals. However, it was found that the increase of SRT only slightly enhanced the removal efficiency in the experiments, since the attached-growth biomass on the roots of water hyacinth was about 60% of total biomass and was not affected by SRT significantly.
3. Either COD or BOD_5 removals in the designed system was comparable with those found in CASPs and NBTPs.
4. While the diluted sewage (COD=30 mg l^{-1}, TKN=6.7 mg l^{-1} and TP=1.0 mg l^{-1}) was used as influent and fed into the aeration-water hyacinth system with a HRT of 10 days, the organic load was not enough to support water hyacinth growing in a healthy condition.
5. The proposed aeration-water hyacinth system behaved a satisfactory capacity of nutrient removal. TKN and TP removal efficiency reached 86% and 80% respectively, which were better than those found in CASPs and NBTPs. Dissimilation via nitrification and denitrification was thought to be a major pathway of N removal in the designed system. Uptake of water hyacinth was supposed to be responsible for more than a half of P removal.

The significance of this development may have a good potential for application in the full scale field conditions either to upgrade the existing conventional biological treatment processes when nitrogen and phosphorus controls are additionally required or to treat municipal wastewater in the rural area or in the developing countries.

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Table 1. Operating conditions in Experiment 1

Bucket	WH (g)	COD (mg l^{-1})	TKN (mg l^{-1})	TP (mg l^{-1})	SRT (d)	HRT (d)	Temp. (°C)	Volume (l)	Air flow (l min^{-1})	Aeration cycle (hr)
No. 1	78	200	45.5	7.0	∞	n.a.	7 - 18	10	4	0.5:0.5
No. 2	80	100	22.8	3.5	∞	n.a.	7 - 18	10	4	0.5:0.5
No. 3	80	50	11.4	1.8	∞	n.a.	7 - 18	10	4	0.5:0.5
No. 4	76	20	4.6	0.7	∞	n.a.	7 - 18	10	4	0.5:0.5
No. 5	76	< 5	0.01	0.01	∞	n.a.	7 - 18	10	4	0.5:0.5

Note: n.a. – not available; ∞ - infinite

Table 2. Operating conditions in Experiment 2

Bucket	WH (g)	COD (mg l^{-1})	TKN (mg l^{-1})	TP (mg l^{-1})	SRT (d)	HRT (d)	Temp. (°C)	Volume (l)	Air flow (l min^{-1})	Aeration cycle (hr)
No. 1	160	258	47.2	8.6	20	6.7	12 - 29	10	4	0.5:0.5
No. 2	170	258	47.2	8.6	10	6.7	12 - 29	10	4	0.5:0.5
No. 3	173	258	47.2	8.6	5	6.7	12 - 29	10	4	0.5:0.5
No. 4	No	258	47.2	8.6	10	6.7	12 - 29	10	4	0.5:0.5

Table 3. Operating conditions in Experiment 3

Bucket	WH (g)	COD (mg l^{-1})	TKN (mg l^{-1})	TP (mg l^{-1})	SRT (d)	HRT (d)	Temp. (°C)	Volume (l)	Air flow (l min^{-1})	Aeration cycle (hr)
No. 1	332	30	6.7	1.0	10	10	19 - 33	33	4	0.5:0.5
No. 2	334	30	6.7	1.0	10	10	19 - 33	33	4	0.5:0.5
No. 3	No	30	6.7	1.0	10	10	19 - 33	33	4	0.5:0.5
No. 4	No	210	44.9	6.6	10	10	19 - 33	33	4	0.5:0.5
No. 5	351	210	44.9	6.6	10	10	19 - 33	33	4	0.5:0.5
No. 6	354	210	44.9	6.6	10	10	19 - 33	33	4	0.5:0.5

Table 4. Characteristics of the raw and settled sewage (Jan. 1995 - Oct. 1996)

Parameter	Unit	Sha Tin WWTP	
		Raw (range)	Settled (mean)
COD	mg l^{-1}	104-391	210
BOD_5	mg l^{-1}	53-273	122
TKN	mg l^{-1}	34-65	45
NH_4^+-N	mg l^{-1}	25-42	37
TP (P)	mg l^{-1}	4.6-11.6	6.6
pH		6.2-8.6	7.3
SS	mg l^{-1}	60-211	72

Figure 1. A sketch of reactors

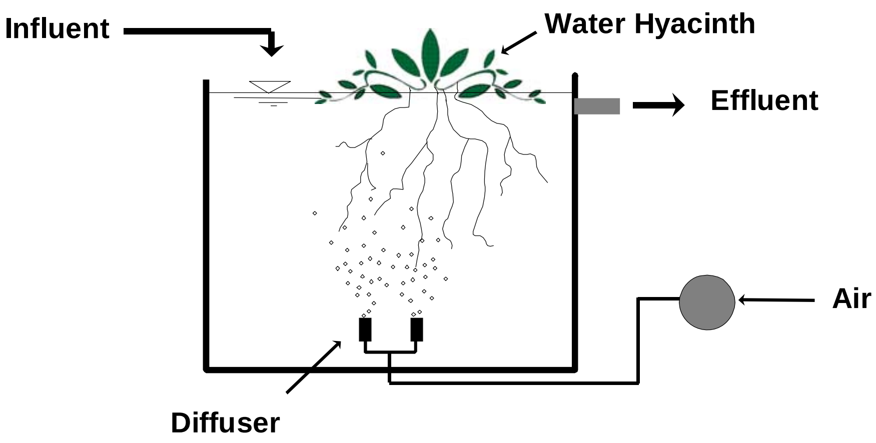

Figure 2. Weight changes of water hyacinth during Experiment 1.

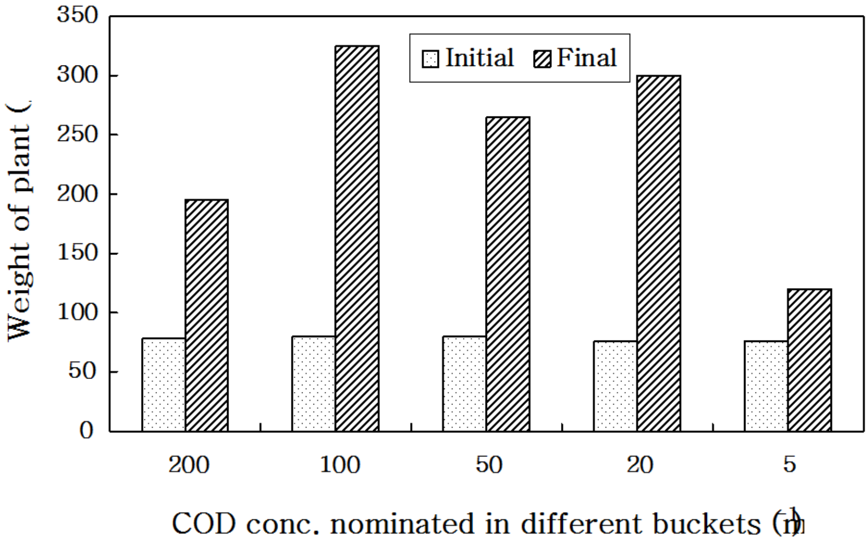

Figure 3. Relations between SRT and removal efficiency.

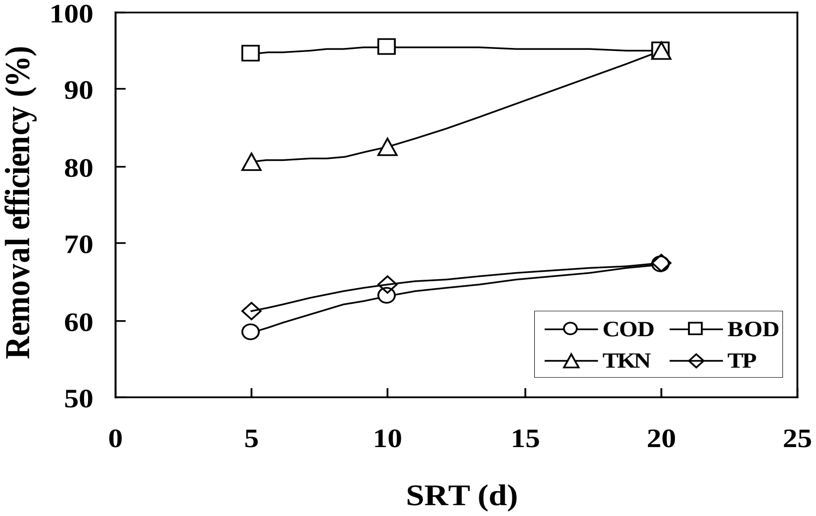

Figure 4. Biomass composition with different conditions in Experiment 3.

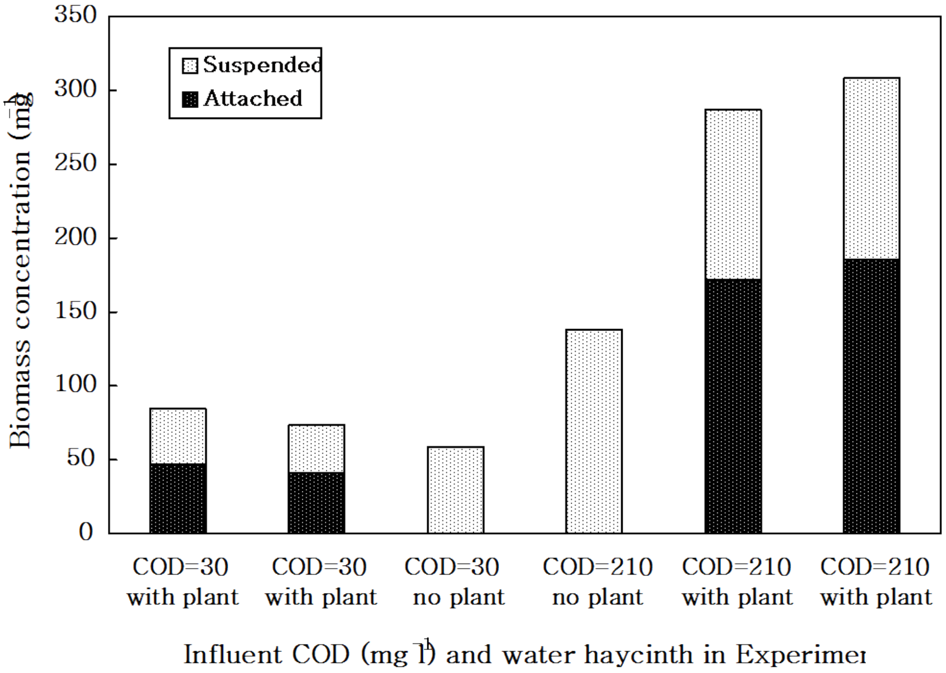

Figure 5. Comparison of COD, BOD, N and P removals in Experiment 2

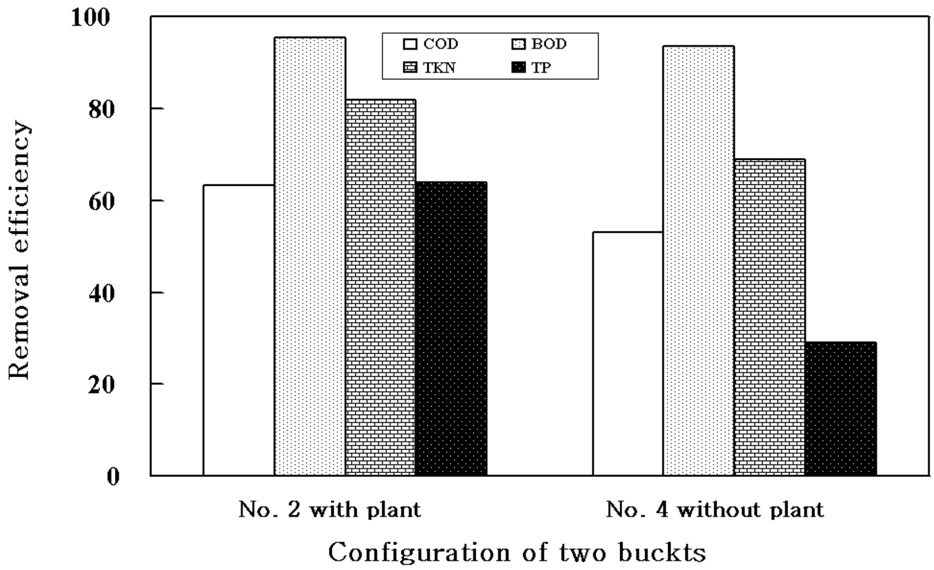

Figure 6. Historical performance of TKN treatment in Experiment 3

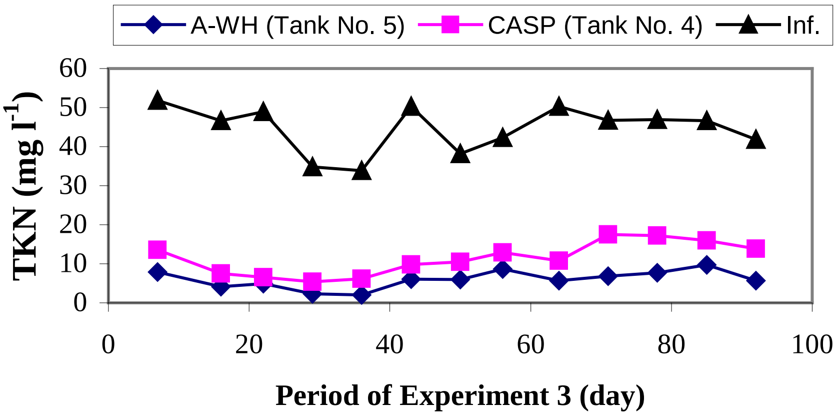

Figure 7. Daily performance of TP treatment in Experiment 3